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FRACTURE ANALYSIS OF EXTERNAL DEFECTS IN THE 105 MM TANK (L7A1)--ETC(U)
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MELBOURNE, VICTORIA

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REPORT

MRL-R-765

FRACTURE ANALYSIS OF EXTERNAL DEFECTS IN THE 105 mm TANK (L7A1) GUN BARREL

Graham Clark

Approved for Public Release

FEBRUARY, 1980

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16. ABSTRACT (if this is security classified, the announcement of this report will be similarly classified):

The use of autofrettage to increase the permissible firing pressures in large calibre gun barrels leads to the development of tensile residual stresses near the external surface of the barrel, and these stresses increase the probability of barrel failure through the growth of a pre-existing defect situated near the tube external surface. Fracture mechanics analyses of such defects necessarily involve estimating the residual stresses in addition to the firing stress distribution in the barrel wall. This report illustrates the way in which such estimates may be obtained and, as an example, a defective barrel is investigated for suitability for use outside normal service conditions, resulting in the proposal that the barrel be used for proof and experimental purposes.

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FRACTURE ANALYSIS OF EXTERNAL DEFECTS IN THE 105 mm TANK (L7A1) GUN BARREL

1. INTRODUCTION

In order to obtain maximum performance (i.e., maximum muzzle velocity) from large calibre guns, it is frequently necessary to use the highest levels of firing pressure which may be contained by the barrel without permanent deformation of the tube wall. It is therefore desirable to use higher strength materials in barrel manufacture and to make full use of the autofrettage process which, by means of a controlled expansion of the barrel forging prior to final machining, can produce considerable increases in the effective strength of the tube [1-3]. In reality, fired barrels contain bore cracks and, if full use is to be made of the barrel's strength, the high levels of hoop stress in the tube wall, acting on a crack-like defect, will produce a crack tip stress intensity which may be sufficient to cause catastrophic failure of the barrel. The likelihood of this critical stress intensity being achieved is further increased by the marked tendency of high-strength materials to possess low toughnesses; a low-strength barrel may be capable of holding together whilst containing a defect which extends completely through the barrel wall, whereas catastrophic failure of a high-strength barrel may occur by unstable growth of a defect less than about ten millimetres in length.

The ability of a defect to extend by fatigue under repeated loading must be seen as significant when high stress-intensities are involved. It is therefore necessary to ensure that barrel integrity is maintained throughout a service life which may include the firing of several thousands of rounds, and hence during the development of a new gun a series of barrels may be fired to destruction in order that a suitable safe life may be determined from the value of fatigue life so obtained. Thereafter, barrels are carefully inspected during manufacture to ensure that no unacceptable defects develop which could cause undue risk of fracture within the established life.

Autofrettage is performed by hydraulically or mechanically expanding the bore of the barrel forging sufficiently to cause a yield zone to spread from the bore outwards, the extent of the plastically-deformed region being limited in some processes by an external containment vessel. After removal of the autofrettage pressure, the elastic recovery of the barrel places much

of the yielded material in residual compression, with this compressive stress being balanced by a tensile residual stress near the barrel exterior. The effect of the residual stress system in service is to reduce the firing stresses near the bore by the amount of the residual compression. Hence, the allowable firing stress which would normally produce permanent deformation of the bore region is increased, and an additional benefit is obtained in that the stresses acting on cracks growing from the bore are reduced, and such cracks will therefore extend at a much lower rate.

The presence of arrays of small thermal cracks around the bore soon after a barrel has entered service leads to the rapid development of bore cracks, and most of the research effort devoted to cracking in gun barrels is centred on cracks growing from the bore outwards. However, the residual tensile stress near the external surface of the barrel (which may be considerable if autofrettage results in plasticity spreading through much of the wall thickness) *increases* the net tensile stress acting in this region when the barrel is fired, and the possibility of there being a stress-concentrator near the surface must be regarded with concern; the increased stress acting on a feature such as a non-metallic inclusion, a change in section, or even a machining mark, can promote the development of fatigue cracks in the region of high stress concentration, or increase the growth-rate of any fatigue crack once initiated.

Cracks in the exterior wall of a barrel have been reported [4], and one site is of particular concern; the longitudinal edge of the interrupted thread which retains the breech ring is a stress concentrator in a highly-stressed part of the barrel, and the possibility of the growth of fatigue-cracks from this feature is clearly significant. This has led to interest in stress-analyses for multiple cracks growing from the outside of an internally-pressurised thick walled vessel (see, for example, reference 5). These analyses have so far ignored, however, the presence of residual stress fields, and are therefore limited in application to non-autofrettaged cylinders. A further complication is that only cylinders of specific wall-ratios have been considered, limiting the usefulness of the analysis to users of barrels with different geometries.

In practice, careful inspection during manufacture and before and after proof firing should reveal the presence of significant defects, and a fracture mechanics analysis involving due consideration of residual stresses may be used to determine whether or not a barrel which contains a defect is suitable for use in any particular firing program. Any uncertain parameters in the analysis must naturally be given conservative values (i.e. those which lead to a low estimate of critical crack length) in order to ensure the integrity of the barrel and hence minimise the risk to personnel and equipment.

This report describes an investigation of external defects in a large-calibre gun barrel, and illustrates the use of fracture mechanics criteria to assess the significance of the defects. In particular, the role of residual stress in the analysis is described in detail.

2. BARREL AND DEFECT GEOMETRY

The barrel considered here is the L7A1 tank gun, which forms the main armament of Australia's force of approximately 100 Leopard AS1 medium tanks. The gun barrel, with a 105 mm rifled bore, is now manufactured in Australia under U.K. licence, using high-quality basic electric arc steel. The manufacturing process includes autofrettage to an internal pressure of 595 - 602 MPa using hydraulic pressure and careful monitoring of barrel expansion in order to ensure that any unsatisfactory deformation behaviour (i.e. excessive expansion, indicating a low-strength region) is detected.

After final machining and inspection, the barrel is proof fired at approximately 426, 490 and 511 MPa (i.e. 100, 115 and 120% of design pressure), these rounds being designated S, P1 and P2 respectively. The exact pressures are measured with copper cylinder gauges inserted with the propellant into the cartridge case.

After proof, the barrel is given a further inspection. The particular barrel considered here was subjected to a magnetic particle inspection which revealed the presence of four defects on the external surface. These defects had the appearance of non-metallic inclusions and were located as shown in Fig. 1.

The maximum size of acceptable surface defects is usually specified for each large calibre gun barrel design but, in this case, defect acceptance levels are left to the judgement of the accepting authority. Reference was made [6] to the specifications for a barrel of similar geometry but higher strength level, in which the maximum acceptable length of surface defect is 6 mm. As the higher strength barrel must have a considerably lower critical crack length than the L7 geometry, it was thought that this 6 mm value would be a suitably conservative value upon which acceptance or rejection decisions could be based, and on this basis defects 1, 3 and 4 were deemed acceptable. Defect 2 lay well outside this limit, and was in the highly-stressed chamber region of the barrel. As a result the barrel was rejected for service by the accepting authority.

A number of barrels are required for proof and experimental purposes (e.g. for proof testing propellant and ammunition components), and as such barrels are invariably used in conditions which preclude any danger to personnel in the event of barrel failure, the possibility of using this barrel for proof purposes was raised. An assessment of defect No. 2 was therefore made.

Consideration of the geometry of this defect showed that the shallow notch produced by grinding, which had been introduced in an unsuccessful attempt to remove the defect, merely increased its stress-concentrating effect, and it was recommended that this notch be removed. A flat was therefore ground on the barrel to the same depth as the notch, and after blending with the barrel surface, had an approximately elliptical shape with dimensions 110 × 35 mm, with the major axis along the length of the barrel. The defect was still visible in the centre of the flat, and the amount of material removed in machining the flat was small enough to be considered negligible.

3. RESIDUAL STRESS DISTRIBUTION

The calculations to estimate upper bound values of the residual stress acting on the barrel wall after autofrettage are described in detail in Appendix A, and the values derived are shown in Figs. A2 and A3.

During final machining after autofrettage, a significant amount of metal which is under high levels of compressive stress is removed from the bore region and in which, as a result, considerable stress redistribution occurs. The effect of this redistribution upon the tensile stress near the barrel exterior is not likely to be significant in barrels which are subjected to partial autofrettage (i.e., those in which the whole wall thickness does not yield), and similarly, the removal of a smaller amount of material from the external wall of the barrel is not likely to cause major changes to the shape of the stress distribution.

4. NET FIRING STRESS

On firing, the elastic hoop stress at radius r induced in the barrel wall (the pressurisation stress) is given by

$$\sigma_p = \frac{P\left(\frac{a^2}{r^2} + 1\right)}{\left(\frac{a^2}{b^2} - 1\right)} \tag{1}$$

where P is the firing pressure acting in a cylinder of internal and external radii b and a respectively. This stress is shown in Fig. 2 for the outer 30 mm of material in the barrel wall, together with the residual stress as derived in Appendix A, and the sum of these stresses gives the total stress in the barrel wall. The pressure assumed in these calculations is 519 MPa, the maximum permissible P2 round pressure.

It is clear that over the 30 mm of depth considered, all three curves in Fig. 2 approximate closely to straight lines; the residual, pressurisation and total stresses are given by

$$\sigma_r = 53 + 763\,x \tag{2}$$

$$\sigma_p = 295 + 4346\,x \tag{3}$$

$$\sigma = 348 + 5109\,x \tag{4}$$

respectively, where all stresses are in MPa, and x in metres. The net stress σ represents the most severe loading which could be applied to a defect growing inwards from the surface of the barrel, and in view of the conservative assumptions made in estimating the residual stress distribution and firing stresses, is unlikely to be achieved often, even in a barrel used for experimental purposes.

5. CRITICAL CRACK LENGTH

For a defect which originates at the external surface of a thick-walled tube, the geometry which gives rise to the most severe crack tip conditions is an infinitely long straight-fronted crack, growing radially towards the bore under the influence of the tensile hoop stress near the surface. Adopting a conservative approach by assuming this geometry, it is relatively simple to estimate the stress-intensity at the crack tip produced by the net stress shown in Fig. 2 and represented in equation (4). The superposition principle allows us simply to add the stress intensities generated by two stress systems, each of which is unaffected by the displacements produced by the other. In this case, as shown in Fig. 3, we add the stress intensity for a uniform stress σ_o acting on the crack of depth x

$$K_1 = 1.12\sigma_o\sqrt{\pi x} \tag{5}$$

to that for a stress which increases linearly from zero at the surface to $\Delta\sigma$ at the crack tip.

$$K_2 = \alpha \, \Delta\sigma \, \sqrt{\pi x} \tag{6}$$

In this case, a suitable value of α is 0.683 [ref. 7], and noting that, from equation (4), σ_o = 348 and $\Delta\sigma$ = 5109x, the net stress-intensity is given in $\mathrm{MPa}\sqrt{\mathrm{m}}$ by

$$K = 691\sqrt{x}\,(1 + 8.953x) \tag{7}$$

where x is in metres. This variation is shown in Fig. 4 for values of x up to 30 mm, and a similar exercise using only the firing stress (i.e. the change in stress on firing each round) gives

$$K = 586\sqrt{x}\,(1 + 8.984x) \tag{8}$$

At the critical value of stress-intensity (the fracture toughness, K_{Ic}) the crack becomes unstable, and barrel fracture occurs. For material conforming to the specifications for this particular gun barrel, however, this fracture toughness is not known; indeed it was not possible to extract from the barrel a fracture toughness test specimen of sufficient size to give the plane-strain crack tip conditions required for measuring a valid K_{Ic} value. At higher strength levels, however, these conditions are more easily achieved, and K_{Ic} may be measured satisfactorily. Such a toughness value is a lower-bound value of the K_{Ic} needed here, and has been measured [8] as 111 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for an L7 gun steel with a 0.2% proof stress (σ_y) of 1100 MPa. To estimate the toughness at a *lower* strength (for this particular barrel σ_y is 919 MPa) a relationship determined for another gun steel [9]

has been used; this showed that toughness increased by 0.115 MPa$\sqrt{m}$ per 1 MPa decrease in yield stress, and when applied to this case, indicates a toughness value (at a σ_y of 919 MPa) of 132 MPa$\sqrt{m}$.

The critical crack length for this toughness value can be seen from Fig. 4 to be 24.5 mm.

6. FATIGUE CRACK GROWTH

Since this critical crack length (x_c) must not be reached at any stage of the barrel's life, it is therefore essential to consider the possibility of a shorter initial crack achieving critical dimensions by fatigue crack growth.

Such growth is controlled primarily by the range of stress-intensity (ΔK) experienced at the crack tip, according to an equation of the form

$$dx/dN = C\Delta K^m \tag{9}$$

where C and m are material constants. In this case, it is clear that residual stress can play no part in controlling fatigue crack extension; the firing stress alone contributes, and the alternating stress intensity is given by equation (8).

It was not possible to obtain values of C and m in equation (9) for the material being investigated here without destroying the barrel, but data was available for a similar gun steel; such values are not likely to lead to widely different growth rate estimates. Here, we use $C = 3.4 \times 10^{-26}$ (in SI units) and $m = 2.5$, where these values have been obtained from growth rate and stress-intensity data in reference 10.

Integrating equation (9) gives, for a crack growing from x_o to x_c over N cycles,

$$N = dN = \frac{1}{C}\int_{x_o}^{x_c} K^{-m}\, dx \tag{10}$$

The 105 mm L7A1 barrel life lies, usually, between 200 and 300 effective full charge rounds; but lives of 1000 or more EFC may be reached with the use of wear-reducing additives. A value of 1000 rounds is used here.

$$N = \frac{1}{10^{15}C}\int_{x_o}^{x_c}\left(586\sqrt{x} + 5261x^{3/2}\right)^{-2.5} dx \tag{11}$$

If for convenience we take a value of 4 mm for x_o and integrate equation (11) numerically, it is possible to construct the curve in Fig. 5 relating crack length to number of cycles (rounds). Clearly, if x_c is 24.5 mm, the length (x_o) of crack which will extend to x_c in 1000 cycles is approximately 21 mm. It is usual to apply a factor of safety of 2.0 to critical crack lengths. Accordingly, the value of acceptable crack length to be used here is approximately 10 mm. It is likely, in view of the approximations made in the analysis, that in some situations cracks deeper than this would be safe; however, a more detailed analysis, requiring data more relevant to this particular barrel, would be necessary to estimate more closely the true critical crack length. On the basis of the above analysis, however, only defects extending less than 10 mm below the surface may be accepted.

7. DEFECT MEASUREMENT

An ultrasonic crack measurement technique was used to estimate the defect size. A specimen from a similar L7A1 barrel was used to calibrate the ultrasonic system for different crack lengths; a flat similar to that around the real defect was machined at the appropriate position, and a sawcut 0.3 mm wide was made in the centre of the flat, using a circular blade of diameter 65 mm. The maximum depth of cut was gradually increased, while the response of a 70° wedge 5 MHz ultrasonic probe, contoured to make close contact with the barrel surface, was noted. The probe was positioned some 83 mm from the sawcut, around the circumference of the barrel; this position had been found to produce the maximum signal height, and the geometry of the system is shown in Fig. 6. Some of the calibration results are shown in Fig. 7.

Measurements were made on the full barrel in exactly the same way, and the maximum signal height was found to be the same as that from a sawcut 0.35 mm deep. The likelihood that a group of non-metallic inclusions will not have exactly the same ultrasonic reflectivity as the calibration sawcut was considered to be of little significance in view of the great difference between the measured and critical crack lengths. The barrel was therefore pronounced 'safe' for a series of proof firings. These firings consisted of three S, six P1 and two P2 rounds, and afterwards, the barrel was again subjected to examination. No change in the ultrasonic response from the defect was detected, and the use of the barrel for proof and experimental purposes was therefore recommended.

8. CONCLUSION

A fracture mechanics analysis has been used to determine a conservative value of critical crack length for an external defect in the chamber region of a 105 mm L7A1 tank gun barrel. This value was then used to determine whether or not the barrel, having failed to meet specification for normal service, could be used for other purposes. The investigation has shown that full use of the barrel could be obtained without the risk of a premature failure and therefore the barrel was suitable for use under proof and

experimental conditions. The role of residual stress in the analysis is seen to be significant and estimates of residual stress should be included in fracture mechanics analyses of autofrettaged large calibre gun barrels.

9. ACKNOWLEDGEMENTS

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APPENDIX A

CALCULATION OF RESIDUAL STRESSES

The barrel was hydraulically autofrettaged to a pressure of P = 595 MPa to produce a yielded zone extending from the bore into the barrel wall. Here, we calculate the hoop stress produced during autofrettage, and by subtracting the 'unloading' elastic stress distribution the residual stress in the wall is determined.

(a) At autofrettage, the section of interest has dimensions (Fig. A1) a = 115.5 mm, b = 49.405 mm, and hence the wall ratio k = a/b = 2.338. In calculating the radius of the yield zone r_y where r_y is *n times the internal* radius b, it is assumed that the material is elastic-perfectly plastic, and hence rather than making use of a flow stress, the materials 0.2% proof stress (919 MPa) is used; this is a conservative criterion which is expected to lead to upper bound estimates of residual stress near the exterior of the barrel [3].

The yield criterion assumed here is an unmodified Tresca criterion, as used by Macrae [2], in which the radial and hoop stresses σ_r and σ_h are related by

$$\sigma_y = \sigma_h - \sigma_r \tag{A1}$$

noting that σ_r has a negative value.

The use of this criterion gives conservative (i.e. more extreme) values of residual stress than the modified Mises criterion [11] which would otherwise be preferred.

We now use

$$\frac{P}{\sigma_y} - \frac{1}{2} + \frac{n^2}{2k^2} - \ln (n) = 0 \tag{A2}$$

to determine the value of n, using an iterative technique for the calculation. In this case, the autofrettage pressure of 595 MPa *leads to* r_y = 68.1 mm.

(b) The plastic zone thus extends from radius b to r_y, as shown in Fig. A1, and we now consider a radius r within this region.

The region between r and a is treated as a separate barrel, under a pressure P_r equivalent to the radial stress at radius r (i.e. $P_r = -\sigma_r$). The value of n for this arrangement is therefore (r_y/r), and the effective k is (a/r). Hence we may determine σ_r from

$$\frac{(-\sigma_r)}{\sigma_y} - \frac{1}{2} + \frac{(r_y/r)^2}{2(a/r)^2} - \ln\,(r_y/r) = 0 \qquad \text{(A3)}$$

for various values of r, and then use equation A1 to determine the hoop stress at this radius.

(c) In the elastic zone ($r_y << r << a$), we consider an elastic barrel of internal radius r_y, under pressure P_y equivalent to the radial stress at r_y (i.e. $P_y = -(\sigma_r)_r$). Then, at radius r

$$\sigma_r = -\frac{P_y\left(\frac{a^2}{r^2} - 1\right)}{\left(\frac{a^2}{r_y^{\,2}} - 1\right)} \qquad \sigma_h = \frac{P_y\left(\frac{a^2}{r^2} + 1\right)}{\left(\frac{a^2}{r_y^{\,2}} - 1\right)} \qquad \text{(A4)}$$

and values of σ_h may be plotted as in Fig. A2 for all r in the real barrel.

(d) On unloading after autofrettage, an elastic stress distribution (equal to that produced by the autofrettage pressure P in a perfectly elastic barrel) is subtracted from the hoop stress distribution obtained above. This "unloading" stress distribution is given by

$$\sigma_u = \frac{P\left(\frac{a^2}{r^2} + 1\right)}{\left(\frac{a^2}{b^2} - 1\right)} \qquad \text{(A5)}$$

and is also shown in Fig. A2.

(e) The sum of the two stress distributions is shown in the same diagram, and represents the residual stress after autofrettage. This is distorted by a further machining process, but as can be seen from Fig. A2, the greatest change in residual stress is likely to be in the bore region; the residual stress changes in the outer wall region are ignored, and the residual tensile hoop stress in the outer region of the finished barrel is shown in Fig. A3.

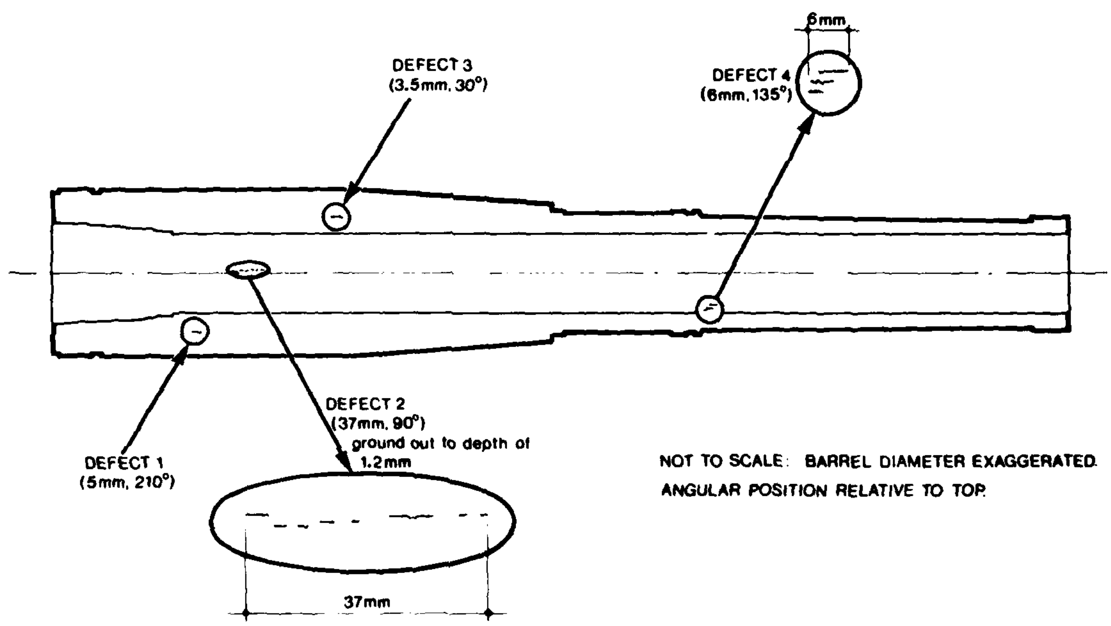

FIG. 1 - The locations of four defective areas on the barrel. The angular positions are measured clockwise (from the breech end) from 'TOP'. The barrel is not to scale.

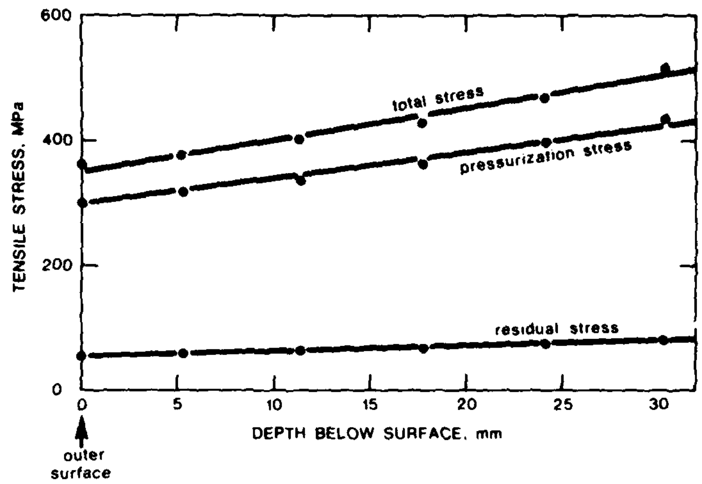

FIG. 2 - Tensile hoop stresses acting near the barrel exterior during firing at a pressure of 519 MPa.

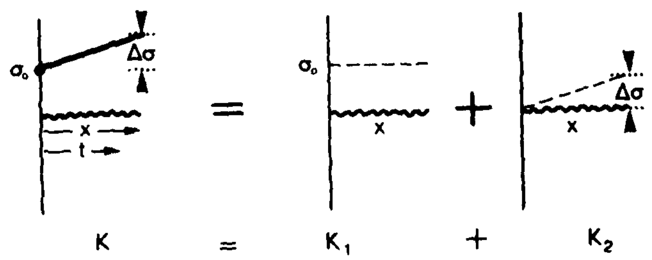

FIG. 3 - Representation of stress intensity for stress field $\sigma = \sigma_o + (t/x)\Delta\sigma$ acting on a surface crack, as the sum of two separate stress intensities resulting from components of this stress field.

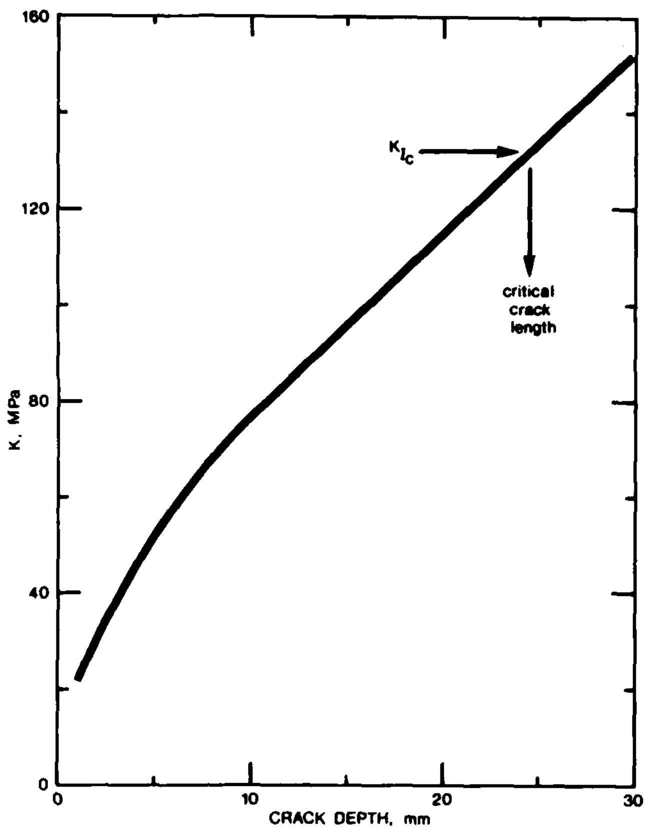

FIG. 4 - Stress intensity at the tip of a straight-fronted surface crack. The applied loading is the sum of pressurisation and residual stresses.

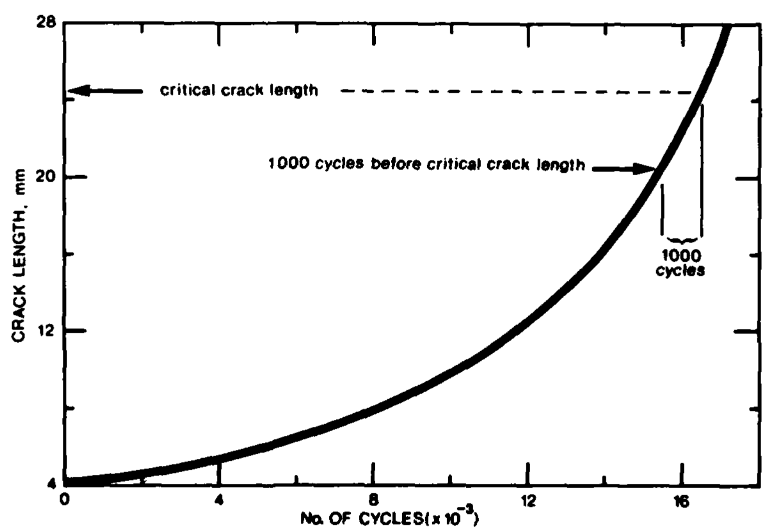

FIG. 5 - The extension of a crack 4 mm deep by fatigue. In 1000 rounds, a crack of critical size (24.5 mm) could develop from a crack some 21 mm deep.

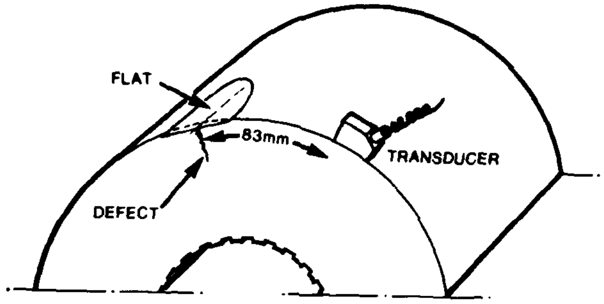

FIG. 6 - Geometrical arrangement of crack depth measurement system.

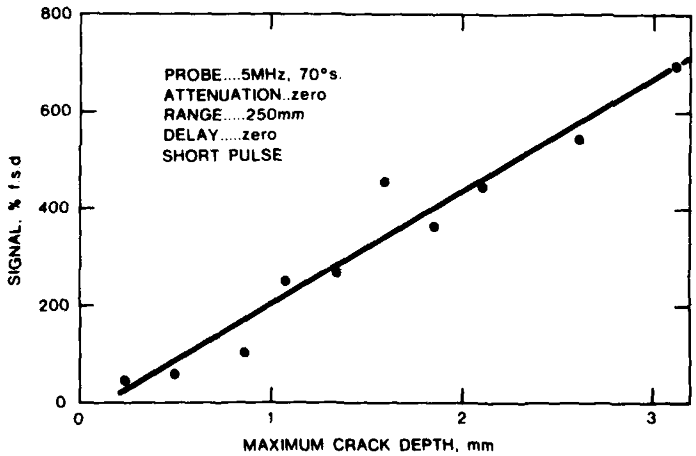

FIG. 7 - Calibration curve for ultrasonic crack depth measurement system, using a 0.3 mm wide sawcut instead of a crack.

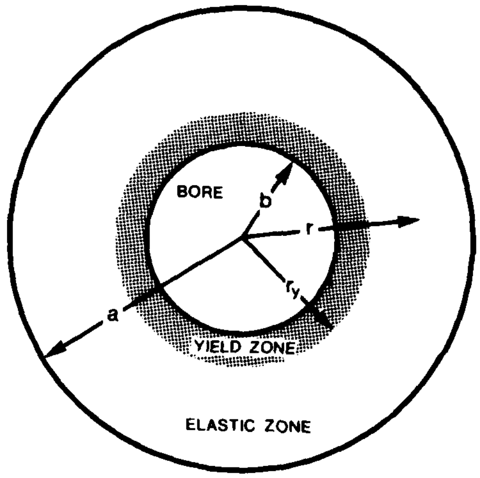

FIG. A1 - Dimensions of the barrel wall section at autofrettage; the plastically deformed material near the bore is shaded.

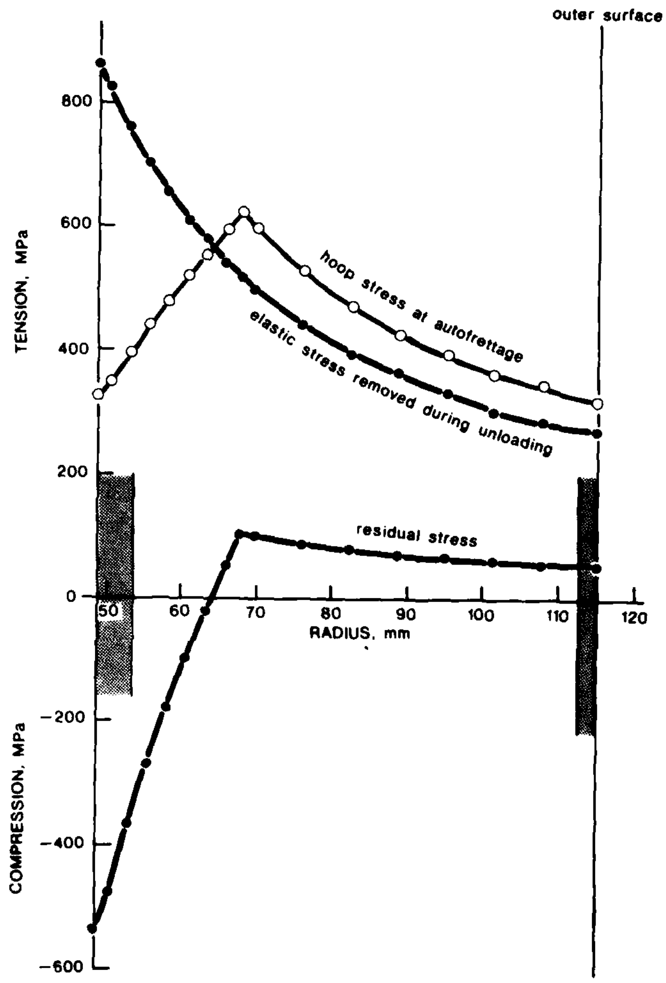

FIG. A2 - Hoop stress at autofrettage, elastic unloading stress, and residual stress distribution. The shaded area represents material removed during the final machining operation.

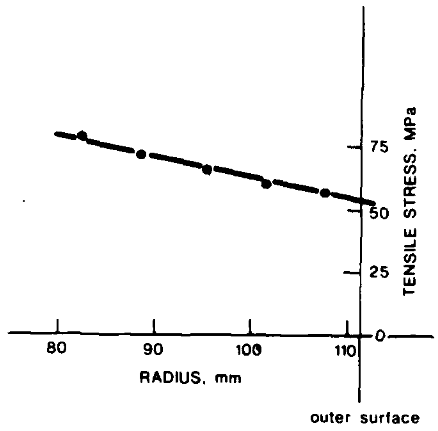

FIG. A3 - Residual stress near barrel surface.

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